THE MARK IX GENERATOR*

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Abstract

A large, explosive-driven helical generator (the Mark IX) is described. The stator ID is 35.6 cm and the armature OD is 17.3 cm. The overall length is 112 cm. This generator delivered 11, 23.5, and 30 MA to 120-, 56-, 35-nH loads, respectively. A Marxing technique is used that enables us to employ over 1 MJ of capacitor bank energy for the initial current without destroying the generator prematurely by magnetic forces. The shot data were analyzed by first computing the generator inductance vs. time curve and then deriving the resistance vs. time curve from the data. This approach yields a useful characterization of the generator.

Introduction

We have reported previously on a large, explosive-driven helical generator[1] patterned after a design by Pavlovskii, et al.[2] This paper describes a new helical generator (the Mark IX) designed to deliver larger currents into lower inductance loads. It has been used as the first stage for a 50-MA coaxial generator[3] and presently constitutes the primary power source for the Los Alamos foil implosion project.[4,5] This paper describes the Mark IX magnetic flux compression generator, gives the test results, and presents a computer model of its behavior.

Description of the Mark IX

Figure 1 shows a schematic drawing of the Mark IX helical generator. The initial current is supplied by a capacitor bank system consisting of two 20-kV, 3000-μF capacitor banks charged in parallel and discharged in series. The Marx bank equivalent is 1500 μF charged to 40 kV. A more complete description of this technique is given in Ref. 5. The explosive charge is detonated at the input end by a plane-wave generator. The timing of the detonator is adjusted so that the generator input is crowbarred by the expanding armature slightly before the initial current reaches a maximum. The armature cone then sweeps toward the output end, compressing the trapped flux and shorting the helical stator turns as it goes.

The stator of the Mark IX is wound with 2/0 (9.3-mm-diameter) solid copper wire. The wire is insulated with shrinkable tubing and formed on a 35.6-cm-diameter mandrel. The turn pattern consists of four sections with a total length of 111.8 cm. The windings start with five equally-spaced parallel wires. Each wire bifurcates at the start of each new section. The layout is given in Table I. The stator section is overcast with concrete to limit the expansion under magnetic forces.

The armature is a hollow OFHC copper tube 17.3 cm in outside diameter with a 9-mm wall. The cylindrical explosive charge fits within the armature. The earlier design used composition B explosive; however, we now use PBX 9501 because of its higher detonation velocity and greater energy. The total length of explosive is 173 cm and the total weight is 60 kg excluding the plane-wave generator.

Table I.

Section	Length (cm)	Number of Turns	Number of Parallel Wires
1	21.7	4	5
2	21.7	2	10
3	22.3	1	20
4	46.1	1	40

Test Results

The first successful test of the Mark IX used a 140-nH load. However, the explosive charge was composition B. The results were not strictly comparable to those of the later two tests that employed 9501. The generator delivered 11 MA to the load. The corresponding peak magnetic energy was 8.5 MJ.

The remaining two characterization experiments employed loads of 56.5 and 35 nH. The loads were coaxial, constructed of 6061 aluminum and designed to be as rugged as possible. Nevertheless, there was probably some expansion by the time peak current occurred. We assumed that the load inductance remained fixed. Two Rogowsky loops were used in each load to obtain the current and dI/dt records.

The current vs. time curves for the two shots are shown in Fig. 2. The corresponding dI/dt records are shown in Fig. 3. The dips caused by wiping across the bifurcations are quite evident. The average initial current for the 56.4-nH load shot was 0.413 MA. The average peak current was 23.5 MA, implying a peak energy of 15.7 MJ. The average initial current for the 35-nH load shot was 0.46 MA. The average peak current was 30 MA, implying a peak magnetic energy of 15.7 MJ. The increased losses resulting from the higher current density in the 35-nH shot decreased the energy multiplication.

Shot Analysis

It is very desirable to be able to model an explosive-driven generator as a variable inductance ($Lg(t)$) in series with a variable resistance ($Rg(t)$). One can then employ a simple circuit code to predict the results when using the generator to power loads that are not fixed inductances (e.g., an opening switch in parallel with an imploding foil). This model is not necessarily complete. If, for example, the magnetic forces are high enough to slow down the armature expansion, then Lg is also a function of the current. Similarly, if the current density in some of the conductors is great enough to heat them to melting, Rg is also dependent on the currents. However, if we do not stray too far from the experimental current loading, we can expect reasonable predictions.

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14. ABSTRACT
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Unfortunately, it is impossible to determine both Lg and Rg from a single experiment. All we can do is to calculate either Lg or Rg and derive the remaining function from the experimental data. We have chosen to calculate $Lg(t)$ and derive $Rg(t)$ from the data. From the circuit equations, we have

$$Rg = -\left[\frac{dLg}{dt}I + (Lg+\lambda)\frac{dI}{dt}\right]/I \quad . \tag{1}$$

I is the load current and λ is the load inductance. If we use the calculated values of Lg and dLg/dt and the experimental values of I and dI/dt, we can obtain $Rg(t)$.

The first step in calculating the generator inductance was to use 2-D hydrodynamics calculations and framing camera photographs to determine the armature cone angle. With 9501 explosive, this angle is 14°. Of course, the shape is not quite that of a perfect cone, but the approximation affects the inductance calculations very little.

Next, the code FCON was used to compute $Lg(t)$ and $dLg(t)/dt$. This code assumes that the generator conductors may be approximated by current sheets and have zero resistivity. The last assumption is obviously wrong from the viewpoint of calculating flux losses, but is a reasonable approximation for determining generator inductance. The armature was divided into zones and each zone represented by a short one-turn cylindrical sheet solenoid carrying a uniform current. The radial velocities in the conical section were given by $v_0 \tan\theta$, where v_0 is the detonation velocity and θ is the cone angle. The radial position of an armature zone is determined by the axial position of the detonation front and the radial velocity. The copper input and output rings were also zoned but remain in fixed positions. The four stator sections were represented as sheet solenoids stacked end to end and connected in series. Since flux is conserved with perfect conductors, we can write

$$(L_s+\lambda)I_s + \sum_{j=1}^{N} L_{sj}I_j = \Phi_s \tag{2a}$$

$$L_{si}I_s + \sum_{j=1}^{N} L_{ij}I_j = 0 \quad , \quad i = 1 \quad , \quad \ldots \quad , \quad N \quad . \tag{2b}$$

L_s is the stator coil self-inductance; L_{sj} is the mutual inductance between the stator coil and zone j; L_{ij} is the mutual inductance between zones i and j; and N is the total number of zones. I_s is the current in the stator-load circuit and I_j is the current in zone j. Φ_s is the total flux linking the stator circuit and is invariant with time. It is determined by solving equation set (2b) with the initial stator current. Then Eq. (2a) gives the flux. The generator inductance is given by

$$Lg(t) = (\Phi_s/I_s) - \lambda \quad . \tag{3}$$

The inductance is obtained by determining the zone positions at time t, computing the inductance matrix, solving for I_s and using Eq. (3). A similar procedure is applied to the time derivatives of Eqs. (2a) and (2b) to compute dLg/dt. The curves for L_g and dLg/dt vs. time are shown for the Mark IX in Figs. 4 and 5. These functions were then applied to the data from the two characterization shots to determine $Rg(t)$. The resultant curves of $Rg(t)$ vs. time are shown in Fig. 6. The two curves track fairly well until about 90 μs after generator start. From that point on, the 35-nH points are substantially higher. This behavior is shown more clearly in Fig. 7. It is evident that the higher current density has increased the flux diffusion into the conductors. Although crude, this model is being used successfully to predict shot results for opening-switch experiments.

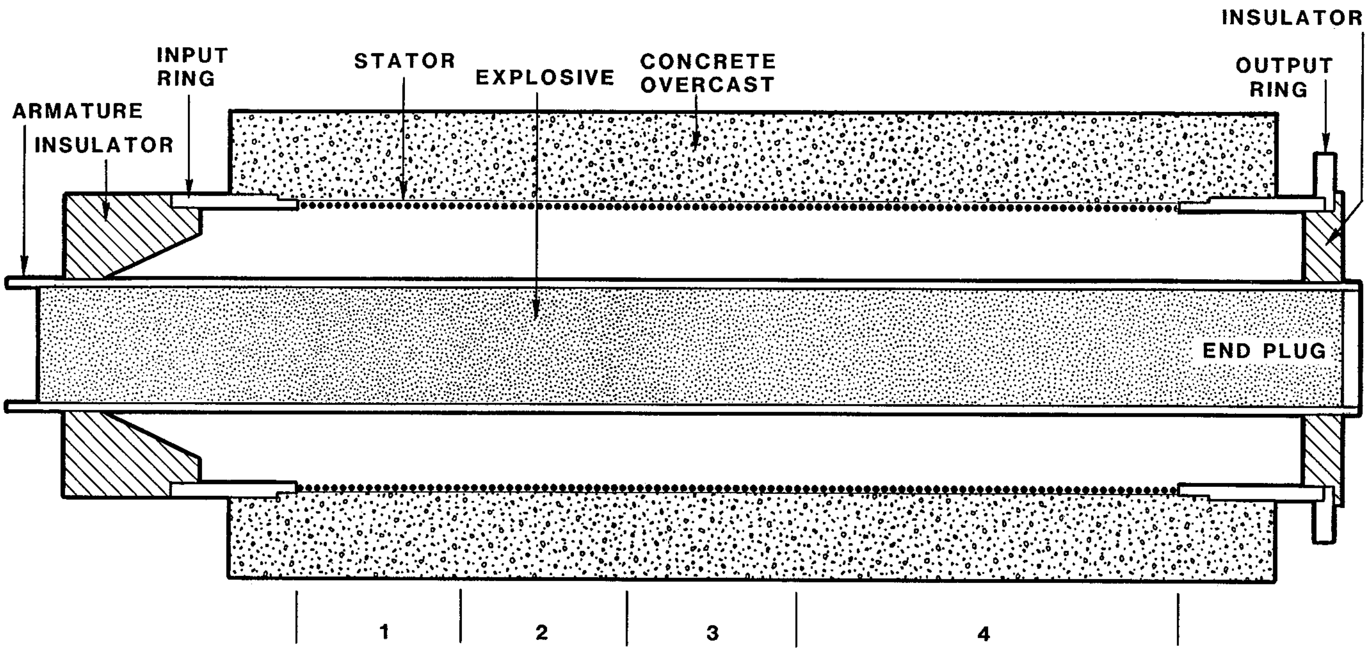

Fig. 1. Schematic cross-section of the Mark IX generator. The numbered segments correspond to the sections in Table I.

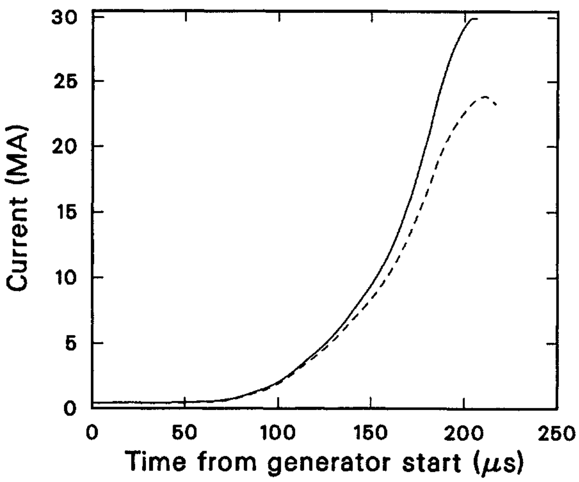

Fig. 2. Current vs. time curves for the Mark IX generator. The solid line follows the data for the 35-nH load; the dashed line is for the 56.5-nH load.

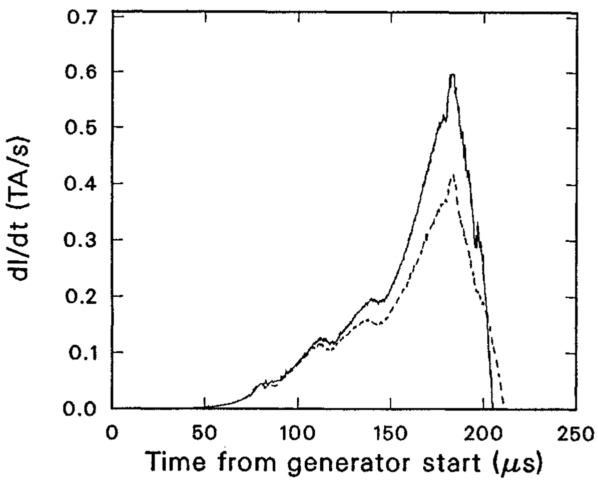

Fig. 3. dI/dt vs. time curves for the Mark IX generator. The solid line follows the data for the 35 nH load; the dashed line is for the 56.5-nH load.

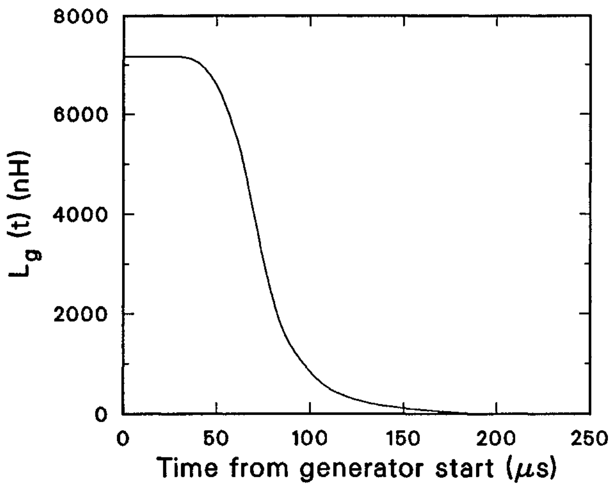

Fig. 4. Calculated generator inductance as a function of time.

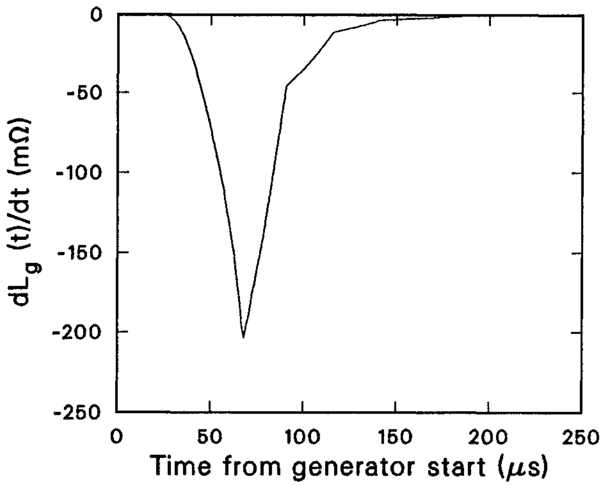

Fig. 5. Calculated dLg/dt as a function of time.

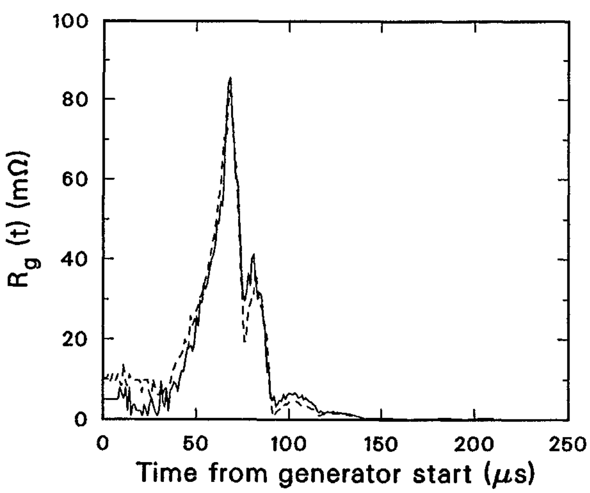

Fig. 6. The solid curve shows the Rg(t) derived from the 35-nH shot; the dashed curve indicates Rg(t) from the 56.5-nH shot.

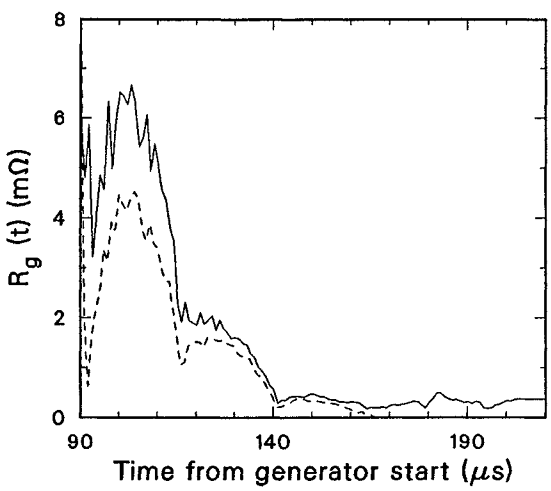

Fig. 7. The solid curve shows the Rg(t) derived from the 35-nH shot; the dashed curve indicates Rg(t) from the 56.5-nH shot.

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